Single Molecule Doping

Buckyballs Properties Change as Single K Atoms Adhere

In a major breakthrough in nanoelectronics, a team led by Michael Crommie has used a scanning tunneling microscope (STM) to attach individual potassium atoms to isolated C_{60} molecules ("buckyballs") to precisely control their electronic properties. Up to seven potassium atoms were added and removed in a controlled manner, demonstrating that the electronic properties of a molecular structure can be reversibly tuned with atomic precision.

The power of modern microelectronics stems from the ability to control the electrical properties of semiconductors. "Doping," the controlled addition of certain impurities, is at the heart of this functionality. For example, in the manufacturing processes of the semiconductor industry, silicon is doped with boron or phosphorous to obtain desired electrical properties, such as conductivity. However, even though device sizes have shrunk considerably over the past few years, thousands of dopant atoms are still needed in a state-of-the-art device. The obvious challenge in nanoelectronics is to scale this process down to the atomic level. Unfortunately, the techniques used now for doping do not scale smoothly to the nanoscale—control of the placement of the dopant atoms remains one of the major challenges in the field and new approaches are needed.

Atomic control here was achieved using a scanning tunneling microscope capable of moving single atoms with great precision. First, widely separated C_{60} molecules and potassium atoms were deposited on the surface of a silver crystal polished to virtually perfect flatness and held at 7 K. Under these conditions, when the tip of the STM is brought close enough to attract individual atoms or molecules, they can be moved at will. The team discovered that when the STM tip was used to move a C_{60} molecule over a potassium (K) atom, the buckyball "picked up" the potassium. Marked changes in the electrical characteristics of the C_{60}-K complex confirmed that the atom was attached in the complex. The same technique was used to add more K atoms, up to a total seven. In a process that has no real analogy in standard IC manufacturing, dopants were also removed. By moving the buckyball over an impurity in the silver surface (thought now to be an oxygen atom), the potassium atoms were "pulled off" one at a time.

The effect of the K atoms is well understood. They add charge to the C_{60} and cause its molecular orbital states to fill with electrons in a manner analogous to the way electrons are reordered in a semiconductor when it is "n-doped" (on a much larger scale) using conventional techniques. Work is continuing to create the opposite electrical effect through "p-type" doping in C_{60} by incorporating atoms which would pull electrons out of the C_{60}. Then a molecular p-type/n-type junction (the most essential solid-state junction) for electronic devices could be made.

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Ryan Yamachika, Michael Grobis, Andre Wachowiak, and Michael F. Crommie, "Controlled Atomic Doping of a Single C_{60} Molecule," *Science* **304** 281 (2004)